A method to assess annual average renewable groundwater reserves for large regions in Spain

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Abstract This paper proposes a method for assessing the renewable groundwater reserves of large regions for an average year, based on the integration of the recession curves for their basins' springs or the natural baseflow of their rivers. In this method, the hydrodynamic volumes (or renewable reserves), were estimated from the baseflow. It was assumed that the flow was the same as the natural recharge, and the recession coefficients were derived from the hydrogeological parameters and geometric characteristics of the aquifers and adjusted to fit the recession curves at gauging stations. The method was applied to all the aquifers of Spain, which have a total renewable groundwater reserve of 86 118 hm^3—four times the mean annual recharge. However, the spatial distribution of these reserves is highly variable; 18.6% of the country's aquifers contain 94.7% of the entire reserve.

Key words renewable groundwater reserves; baseflow; Spain

Une méthode pour évaluer annuelle moyenne des réserves en eaux souterraines renouvelables pour les grandes régions en Espagne

Résumé Cet article propose une méthode pour évaluer les réserves en eaux souterraines renouvelables de grandes régions pour une année moyenne, basée sur l'intégration des courbes de récession des de leurs bassins versants ou le débit de base naturelle de leurs rivières. Dans cette méthode, les volumes hydrodynamiques (ou des réserves renouvelables), ont été estimés à partir du débit de base. On a supposé que le débit était le même que la recharge naturelle, et les coefficients de récession ont été calculées à partir des paramètres hydrogéologiques et les caractéristiques géométriques des aquifères et pour s'adapter à la récession des courbes dans les stations de jaugeage. La méthode a été appliquée à tous les aquifères de l'Espagne, qui ont une réserve totale d'eau souterraine renouvelable de 86 118 hm^3—quatre fois la recharge annuelle moyenne. Cependant, la répartition spatiale de ces réserves est très variable; 18.6% des aquifères du pays contiennent 94.7% de toute la réserve.

Mots clefs réserves en eaux souterraines renouvelables; débit de base, Espagne

1 INTRODUCTION AND OBJECTIVES

The regulation of the water supply in order to approximate it to the demand of a specific area must take into account not only seasonal variations within the hydrological year, but also inter-annual variations. This regulation is largely based on the use of surface reservoirs and the exploitation of aquifers. The former are mainly used to compensate for the annual variation in water resources, while the latter, given their very large storage capacity, can be used to compensate for both annual and inter-annual variations. Water resource managers normally consider aquifers to be hyper-reservoirs. The assessment of groundwater reserves at large spatial scales is a subject of interest for water resource management science.

The management of an aquifer comprises management of the flow and volume of the stored water. The latter variable is of particular interest in Spain, one of the most arid countries in Europe, where drought is common. Since they are less vulnerable to drought than rivers and surface reservoirs, the large aquifer reserves guarantee the water supply—as long as they are not over-exploited. The vulnerability of a given aquifer to droughts depends on how quickly the aquifer is able to store and discharge water. Aquifers are more vulnerable when they transfer groundwater very quickly to discharge areas. Recession curves allow evaluation of this feature. In other words, the vulnerability of aquifers to drought is related to how quickly they discharge stored water, which in turn depends on recession coefficients (Estrela, 2006). An adequate summer water supply is of great importance to Spain where the main source of national income is tourism; most of the country's annual 60 million visitors come at this time when the drought is at its worst and urban demand for water at its highest.

It is important to understand both the country's water resources and its reserves, at least those of the main aquifers destined to supply the population. This would allow plans to be made regarding how to act in emergencies, especially in those basins most vulnerable to drought.

Changes in underground water constitute a critical component of the terrestrial water budget. Baseflow data can provide a quantitative estimate of the basin-scale groundwater storage changes that have taken place over the period of record (Brutsaert, 2008; Brutsaert & Sugita, 2008).

From a practical perspective, storage capacity is one of the most important features of aquifer systems. This is because it makes them dependable resources during droughts, while also guaranteeing suitable river baseflows in the absence of recent rainfall. However, it is complex to assess the overall storage capacity of an aquifer. This is because of the practical difficulties involved in determining the detailed geometry of aquifers, as well as in quantifying hydrodynamic parameters, such as permeability or storage coefficients, sufficiently accurately. Thus, attempts to quantify groundwater resources usually aim at establishing reserves to a given depth below surface. The methodology at hand simplifies these problems by using recession coefficients.

To date, the estimates made in Spain regarding the total reserves of subterranean water, some 200 000 hm^3, have been preliminary and have only taken into account the first 200 m below-surface depth (ITGE, 1995). The present work describes a means of calculating part of the true subterranean reserves—the renewable reserves, or those lying above the natural drainage level of these aquifers.

Renewable aquifer reserves can be estimated based on discharges through springs and streams. This has often been done in individual aquifers, but seldom at the regional or national scale due to the absence of sufficiently comprehensive data. This paper presents a methodology to estimate renewable groundwater reserves based on baseflow recession coefficients. Basin-scale results are calculated by means of an analytical model and interpreted according to the main features and aquifer units of each catchment.

2 METHODOLOGY

2.1 Terminology

The natural recharge (R) of an aquifer is defined as that part of the infiltrated water that feeds the aquifer. According to the hydrological balance of an aquifer, R is equal to the exiting volume per unit time (Q) plus or minus the variation in groundwater storage (ΔA):

$$R = Q \pm \Delta A \quad (1)$$

For long periods of time, the R of an aquifer may equal the mean discharge, since ΔA is zero. Equation (1) therefore becomes:

$$R = Q \quad (2)$$

Thus, in general, the natural recharge rate of an aquifer is equal to its water output. The groundwater reserve is divided into permanent reserve (W_p) and renewable reserve (W_r), where the latter is the hydrodynamic volume (V) that represents the quantity of water stored in an aquifer above its drainage level at a specific time (Fig. 1).

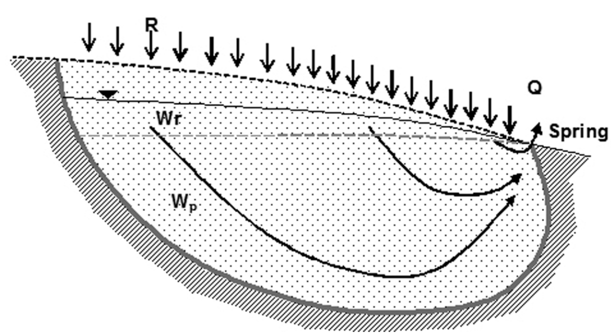

Fig. 1 Conceptual model of an aquifer distinguishing recharge, R, from the exiting volume, Q, the hydrodynamic volume or renewable reserve, W_r, and the permanent reserve, $W_{p.}$.

2.2 Proposed calculation method

The methodology proposed for calculating W_r is based on the calculation of V, which can be obtained at any given moment from the recession curve of a basin's springs or the baseflow of its rivers (uninfluenced).

For a confined or non-confined aquifer of considerable depth and with constant level of discharge, the uninfluenced drainage is obtained by:

$$Q_t = Q_0.e^{-\alpha t} \tag{3}$$

where Q_t is the volumetric rate of flow, Q_0 is its value at the (arbitrarily) chosen reference of time, i.e. $t = 0$ and α is the recession coefficient (Boussinesq, 1877). The latter is expressed as (Rorabaugh, 1960):

$$\alpha = 2T/SL^2 \tag{4}$$

This value is influenced by the hydrogeological characteristics, i.e. transmissivity (T) and storage coefficient (S), as well as a characteristic geometric size of the aquifer, i.e. the length (L) from the aquifer's centre of gravity to the discharge point, or, when possible to define, the average length of flowpaths.

Given the form of equation (3), drainage would be slow, influenced by the regulatory nature of the springs or rivers fed by the aquifer. For the flow to be reduced by one half, a time of $t = 0.693/\alpha$ would be necessary. With values of $\alpha_1 = 0.01$ d^{-1} or $\alpha_2 = 0.001$ d^{-1}, a time t_1 of 69 days and t_2 of 693 days would be required.

Under undisturbed conditions, recession in most aquifers is described by equation (3). Most aquifers present one single recession coefficient, but some may have several. Boussinesq (1904), Barnes (1939), Drogue (1967, 1972), Schöeller (1967), Singh (1968), Hall (1968), Mangin (1970) and Tallaksen (1995), explain the hydrological significance of recession curves.

To obtain the groundwater level volume contained in an aquifer above the spring level or V in any given instant during the recession period, we integrate the expression (3) between zero and infinity:

$$V_{t0} = \int_{t_0}^{\infty} Q_t \mathrm{d}t = \int_{t_0}^{\infty} Q_0 \cdot e^{-\alpha t} \mathrm{d}t = \frac{Q_{t0}}{\alpha} \tag{5}$$

where Q_t is the flow in the instant t, Q_0 the flow at the beginning of the recession curve ($t_0 = 0$), t is time and α the recession coefficient.

2.3 Some limitations of this approach

Aside from the limitations proper to a simplification of reality, this method presents some relatively minor shortcomings which may constrain its application to other aquifers. These are outlined below:

(a) Equation (3) is based on approximating an aquifer as a linear box, where discharge is linearly proportional to mean head above the discharge point. In reality, however, discharge may be best approximated as:

$$Q = \sum r_i \mathrm{e}^{-\alpha_i t} \tag{6}$$

where r_i results from distributing total recharge according to the aquifer eigenvalues, α_i (Sahuquillo & Andreu, 1988). While this is well known, equation (3) is still used for approximating the recession curve of hydrographs because rainless periods are moderately long, so that most aquifer response modes are never activated under natural conditions. However, extrapolating this single exponential behaviour to infinite time leads to an underestimation of V.

(b) One single recession coefficient is considered, although it is known that aquifers sometimes present several. In any case, in most cases the main recession coefficient corresponds to gradual (slow) emptying.

(c) This method assumes that the discharge through springs and rivers constitutes the only system outflow, but does not consider the lateral groundwater transfer between adjacent aquifers. These are small in Spain.

(d) Equations (1) and (2) ignore any effects of groundwater losses to evaporation. In the discharge area the equation becomes:

$$Q = R - E \tag{7}$$

where Q is the groundwater component of average annual runoff (or average annual baseflow), R the average annual groundwater recharge, and E the average annual evapotranspiration from the discharged area. This effect has not been quantified. However, the effect is thought to not be very relevant in Spain; as this is a very arid country, the groundwater level is deep and discharge areas are usually located at very specific points, so the E affects only a very reduced area of the total surface of the country.

3 USE OF THE METHODOLOGY IN SPAIN

Spain (excluding the Canary Islands) has an area of 497 477 km^2, of which 165 000 km^2 are occupied by large aquifers. Some 74 968 km^2 are carbonate in nature and a further 90 125 km^2 detritic (MOPU, 1990). The remaining area is composed of low permeability rocks.

From a practical standpoint, this methodology comprises the following steps:

- The average annual recharge, R, is estimated for each of Spain's 349 hydrogeological units. This is achieved through a distributed mathematical model and takes into account data records spanning 1940–1990 (MIMAM 2000). Recharge is calculated from equation (2), where the term Q, corresponds to river flows at the beginning of the recession curve (Q_{t0}).
- The main recession coefficient (α) is obtained from four different sources:
  - (i) known spring discharges;
  - (ii) river hydrographs at over 100 gauging stations located downstream of the main aquifer systems;
  - (iii) hydrodynamic parameters and aquifer geometry; and
  - (iv) the SIMPA model (Ruiz, 1998), which uses recession coefficients obtained from sources (i), (ii) and (iii) (MIMAM 2000). Modelled hydrographs were calibrated against field data (rainfall, air temperature, lithology, etc.).
- Groundwater reserves are calculated using equation (5).

3.1 Calculation of mean flows

The data provided by the *Libro Blanco del Agua* (MIMAM, 2000) was used for all of Spain's hydrogeological units. The procedure used to determine R or Q (uninfluenced) was distributed modelling of the basic components of the hydrological cycle on a countrywide scale for 1940–1990. This model makes use of the information recorded at gauging stations, weather data, and the characteristics of the aquifers examined. The conceptual, distributed hydrological model (which takes into account the spatial variability of all the hydrological data) can simulate the mean monthly flows (uninfluenced) at any point in the country's hydrographic network by reproducing the essential processes of water transport in the different phases of the hydrological cycle. In each of the approximately 500 000 cells of dimensions 1000 × 1000 m into which Spain can be divided, it uses the principle of continuity and establishes the laws of transfer and sharing between the different storage zones on a monthly scale (Estrela *et al.*, 1999).

The model inputs used in the present work were monthly rainfall and temperature data. Data from flow gauging station records were taken as simulation or calibration points. Also taken into account were the maximum moisture storage capacity of the soil, the maximum infiltration capacity, and the recession coefficients of the aquifers. With respect to the infiltration capacity, the recharge estimates of the lithological groups reported by Sanz (1996) were used.

3.2 Estimation of Q_0

The value of V for any aquifer varies over time; the moment for measuring this variable must therefore be chosen. Let us assume that this is the dry season. For this precise moment, it has been shown in many cases in Spain that the flow Q_0 is 75% of the annual mean. This reduction factor is an approximation valid to many aquifer systems in Spain, as shown by different studies and technical reports. Hence, an approximate figure is considered to be sufficient. Therefore in this work V_{t0} was measured when $Q_0 = 0.75Q$.

As shown later (Section 4), using this assumption, Spain's total reserves amount to 86 118 hm^3. Taking $Q_0 = Q$, the renewable reserves would amount to 114 782 hm^3.

Since α is expressed in d^{-1}, average flows must also be expressed as a function of time. In turn, recharge (R) is measured in hm^3/year. Therefore $Q_0 = 0.75 \times R/365$ hm^3/year, and $V = (0.75R/\alpha)/365 = 2.055 \times 10^{-3}$ R/α. This expression has been used for the calculations. Values for α are given in Table 2.

3.3 Determination of recession coefficients

Recession coefficients have been obtained in four different ways. Priority was given to the first approaches over the later ones.

(a) Existing knowledge on aquifer parameters, particularly regarding hydrogeological reports and scientific papers.

(b) Analysis of baseflow recession curves for 87 gauging stations located downstream of the main aquifer systems. Hydrographs correspond to rivers whose natural regime is not altered by anthropic actions. Also, records for 29 stations have been corrected to the natural regime (MIMAM, 2000). Overall, the uneven spatial distribution of gauging stations implies that some of them deal with a single aquifer, whereas others account for several. In addition, the influence of surface runoff is highly variable from one place to another. However, marked recession curves are common, as corresponds to a predominantly semi-arid climate.

(c) Estimation of recession coefficients as a function of aquifer area and geometry (L) based on equation (4). Many of the required parameters have been obtained from ITGE (1998). Equation (4) can also be combined with other approaches such as Darcy's law. As an example, the case of the Alhama aquifer is considered. This system presents an elongated shape, and discharges through a series of springs with an average flow $Q = 450$ L/s (Sanz & Yélamos, 1998). Other known data include: the average porosity ($m_e = 1.4\%$); the distance from the centre of the recharge area to the springs ($L = 40$ km); the age of spring water (40 years) obtained from tritium analyses; the hydraulic gradient ($i = 0.0055$); and the average breadth of the aquifer ($a = 1330$ m). Water velocity ($V_r = L/t = 1$ km/year), combined with effective porosity and the hydraulic gradient, yields an average permeability of 6.64 m/year ($K = V_r m_e / i$). Transmissivity is thus estimated taking a saturated thickness, b, that equals Q/iKa, to obtain a value of $T = 5312\ \mathrm{m^2/d}$. Hence, the resulting recession coefficient is:

$$\alpha = \frac{2\,T}{S\,L^2} = \frac{2 \times 5312\ \mathrm{m^2/d}}{0.014 \times (40000\ \mathrm{m^2})} = 0.000474\ \mathrm{d^{-1}} \tag{8}$$

(d) As there were not enough stream gauging stations in all aquifer systems, the SIMPA model (Ruiz, 1998) was used in some cases. This model, which is calibrated under natural conditions, considers aquifer systems as reservoirs that may receive infiltration across their areal extent. Aquifers discharge through streams and springs according to an exponential law. For each aquifer, this assumes discharge to be proportional to one single parameter (the recession coefficient). Recession coefficients were adjusted by fitting model hydrographs to observed records. They were also compared to the α values obtained by the above procedures.

4 RESULTS

The V_{t0} of Spain's aquifers is some 86 118 hm^3, i.e. about four times the annual recharge. If this were distributed across the entire permeable surface area, a layer of water about 0.5 m deep would be obtained. However, the spatial distribution of V_{t0} values can be highly variable, which influences the value of α. Thus, for a recharge of 10 hm^3/year, V_{t0} values of 51.7 hm^3 would be obtained for $\alpha 10^5 = 20$ d^{-1}, or 1 hm^3 for $\alpha 10^5 = 2000$ d^{-1}; the α value for Spain's aquifers certainly varies between $\alpha 10^5 = 1$ d^{-1} and $\alpha 10^5 = 10\,000$ d^{-1}.

Figure 2 classifies the 349 hydrogeological units studied into six groups according to their α values. Table 1 classifies the 349 hydrogeological units studied into three groups according to their α values. The influence of this coefficient is clearly seen: 65 units have an $\alpha 10^5$ value of ≤ 100 d^{-1}. With a R value between them of 3443 hm^3/year (17.1% of the entire recharge), the value of V_{t0} reaches 77 855 hm^3. This amount represents 94.7% of the total hydrodynamic volume of all the aquifers. In contrast, 39 hydrogeological units have $\alpha 10^5 \geq 2000$ d^{-1}; with recharge of 3020 hm^3/year (15.7% of the total recharge), the V_{t0} value reaches only 226 hm^3—less than 0.3% of the total volume.

Two basins stand out in that together they harbour 83% of all the hydrodynamic reserve—the Duero basin, with a volume of 30 942 hm^3, and the Júcar basin, with a volume of 40 604 hm^3. In these basins the mean $\alpha 10^5$ values are 12 and 18 d^{-1}, respectively, compared to the general mean of 46 d^{-1}. The Duero basin is home to hydrogeological units such as Rañas del Orbigo, Esla, Cea-Carrión, and in particular Esla-Valderaduey with $\alpha 10^5$ of less than 2 d^{-1}. The Júcar basin contains the Mancha Oriental hydrogeological unit, with $\alpha 10^5$ of 8 d^{-1}. If the last two aquifers are removed from the general calculation, the V_{t0} value falls from 86 118.5 hm^3 to 49 808 hm^3. In addition, and as far as the rest of the basins are concerned, the Ebro, Segura and Guadalquivir basins stand out with V_{t0} values of 3712, 2639 and 2610 hm^3, respectively.

The total V_{t0}—an estimated 86 118.5 hm^3—has a corresponding mean α of 0.00046 d^{-1}. This reflects a flow of $Q_0 = V_{t0}\,\alpha = 39.7$ hm^3/d. This flow would be reduced to half this value under non-uninfluenced conditions, when $t_0 = 0.693/\alpha = 1506$ d. This inertia can be explained by the influence of large

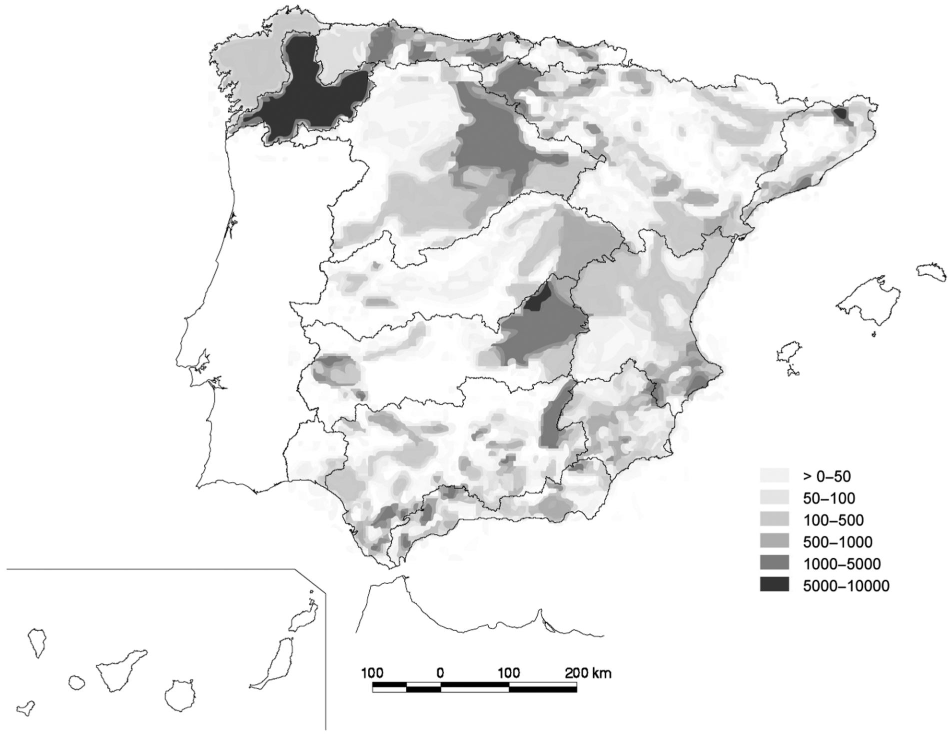

Fig. 2 Map of recession coefficients $\alpha 10^5$ in d^{-1} (adapted from MIMAN, 2000).

low-permeability detritic aquifers that form the Tajo and Douro depressions. It is also a consequence of the existence of large karst systems, such as the upper Jucar basin, where groundwater velocities compensate for long flowpaths. It is known that karst aquifers usually have high recession coefficients, which reduces values, as opposed to what happens with detritic aquifers.

The hydrogeological units of Spain have been classified into four groups, according to their recession coefficients, as shown in Table 2. Of the 349 recession coefficients, 203 correspond to calcareous aquifers and 136 to detritic aquifers. The majority of these aquifers (62%) have recession coefficients of 0.001–0.01 d^{-1}, but among those composed of calcareous rock 82% of the recession coefficients lie between 0.001 and 0.02 d^{-1} compared to just 54% for the detritic aquifers. Thus, the more extreme values are associated with detritic aquifers, which is quite logical given the greater difficulty water has in circulating in certain detritic materials. Twenty one calcareous aquifers and 44 detritic aquifers have values of $\alpha \leq 0.001$ d^{-1}. However, it is more common for detritic aquifers (generally the infilling of large sedimentary basins) to have values of $\alpha \geq 0.02$ d^{-1}.

One hundred aquifers are outstanding in that their values are either $\alpha \leq 0.001$ d^{-1} ($n = 61$) or $\alpha \geq 0.02$ d^{-1} ($n = 39$). The former can store large amounts because of their slow drainage speed in an uninfluenced regime; they are therefore not very vulnerable to drought. In contrast, the other 39 cannot store as much water because of their faster drainage speed; they are therefore more vulnerable.

5 CONCLUSIONS

The total renewable resources, which correspond to a significant share of the total groundwater reserves, can be used to study baseflows and to evaluate the effects of slow aquifer discharge. This is of particular importance in semi-arid countries, where streamflows are highly variable. It also contributes to a better understanding and management of intensively-exploited aquifers and to evaluation of their resilience to droughts.

This work proposes a method for assessing the renewable groundwater reserves of a large region for an average year, based on the integration of the recession curve of its springs or the baseflow of its rivers (uninfluenced). The values of recharge or flow are

Table 1 Recharge and hydrodynamic volume: (a) for Spain as a whole, and (b) by basin. (c) Characteristics of Spain's basins.

Intervals of α 10^5	Number of hydrogeological units	Mean α 10^5	Area of Spain	Recharge	Hydrodynamic volume			Recharge
(d^{-1})		(d^{-1})	(km^2)	(hm^3/year)	(hm^3)	(L/m^2)	(%)	(L/m^2)
(a) For Spain as a whole.								
$A10^5 \leq 100$	65	9.1	46 400.8	3 443	77 562	1 668	90.0	7.4
$100 < \alpha 10^5 < 2000$	245	315	87 769.8	12 805	8 330	95	9.7	145.9
$2000 \leq \alpha 10^5$	39	2 379	30 823.4	3 020	226	7	0.3	98.0
	349	47.7	165 093	19 268	86 118	522	1 000	116.7

	Recharge (hm^3/year)			Hydrodynamic volume (hm^3)			Mean α 10^5		
	$a10^5 \leq 100$	$100 < \alpha 10^5 < 2000$	$2000 \leq \alpha 10^5$	$\alpha 10^5 \leq 100$	$100 < \alpha 10^5 < 2000$	$2000 \leq \alpha 10^5$	$\alpha 10^5 \leq 100$	$100 < \alpha 10^5 < 2000$	$2000 \leq \alpha 10^5$
(b) By basin (α in d^{-1})									
1 Norte	148	1 736	1 044	1 433	389	96	21.0	915	2 222
2 Duero	260	1 479	137	30 032	899	11	1.8	337	2 500
3 Tajo	62	1 753	–	221	1 132	–	63.1	316	–
4 Guadiana	98	188	448	609	88	13	33.0	438	7 119
5 Guadalquivir	509	1 262	570	1 812	762	36	57.6	339	3 230
6 Sur	121	949	300	456	373	24	54.5	521	2 587
7 Segura	368	180	2	2 519	120	0	29.9	307	2 606
8 Júcar	953	2 365	178	37 643	2 946	15	5.1	164	2 472
9 Ebro	883	2 053	173	2 623	1 071	18	68.8	393	2 000
10 Pirineo O.	35	830	167	214	521	13	9.1	327	2 574
	3 443	12 805	3 020	77 562	8 330	226	9.1	315	2 739

	Area (km^2)	Recharge (hm^3/year)	Hydrodynamic volume				Recharge (L/m^2)
			(hm^3)	(L/m^2)	Mean α 10^5	%	
(c) Basin characteristics (α in d^{-1}).							
1 Norte	7 009	2 927.5	1 918.3	274	313	2.2	418
2 Duero	53 723	1 875.5	30 942.2	576	12	35.9	35
3 Tajo	16 951	1 815.0	1 359.0	80	274	1.6	107
4 Guadiana	11 960	734.0	732.9	61	205	0.9	61
5 Guadalquivir	13 215	2 341.2	2 610.2	198	184	3.0	177
6 Sur	4 634	1 369.8	852.8	184	329	1.0	296
7 Segura	9 168	550.5	2 639.2	288	43	3.1	60
8 Júcar	24 996	3 495.5	40 603.8	1 624	18	47.1	140
9 Ebro	18 963	3 109.0	3 711.8	196	172	4.3	164
10 Pirineo O.	6 474	1 031.2	748.3	116	283	0.9	159
Total	165 093	19 268.2	86 118.2	522	46	100.0	117

Table 2 Distribution of recession coefficients (α) values by basin, rock type and size (α in d^{-1}).

Basin	$\alpha 10^5 \leq 100$		$100 < \alpha 10^5 < 1000$		$1000 < \alpha 10^5 < 2000$		$\alpha 10^5 \geq 2000$		Totals		
	Calcareous	Detritic	Calcareous	Detritic	Calcareous	Detritic	Calcareous	Detritic	Calcareous	Detritic	All
1 Norte	1	2	11	–	3	3	2	2	17	7	24
2 Duero	–	5	7	6	1	–	–	2	8	13	21
3 Tajo	–	2	6	5	–	–	–	–	6	7	13
4 Guadiana	–	1	5	2	–	–	–	4	5	7	12
5 Guadalquivir	–	9	28	11	3	1	3	9	34	30	64
6 Sur	1	7	16	16	4	1	3	2	24	26	50
7 Segura	9	4	19	2	1	–	1	–	30	6	36
8 Júcar	4	6	24	8	5	2	3	–	36	16	52
9 Ebro	6	6	22	7	1	1	3	1	32	15	47
10 Pirineo O.	–	2	7	14	3	–	1	3	11	19	30
Total	21	44	145	71	21	8	16	23	203	146	349
Percentages	10.3	30.1									

estimated and the coefficients of recession determined for 349 hydrogeological units in Spain.

In this method, the renewable reserves were estimated from the recession curve equation. It was assumed that the flow was the same as the natural recharge, and that the recession coefficients were derived from the hydrogeological parameters (transmissivity and storage coefficient), and geometric characteristics of aquifers, and adjusted to fit the recession curves at gauging stations.

Recharge is calculated by means of a distributed model which takes into account all elements of the water cycle under natural conditions. The model adopts monthly time steps, and is valid for areas where permeable outcrops are found. Recession coefficients have been obtained from local and regional-scale studies in some cases. In others, these have been estimated from aquifer area and geometry, as well as from average values for the hydrodynamic parameters. These values were in turn adjusted during the model calibration process, based on natural-regime stream recession curves.

This method has been applied to all of Spain's permeable units, whose total renewable reserves have been estimated at 86 118 hm^3 (39.6 hm^3/d at the beginning of the recession period). Under undisturbed conditions, this would decrease to approximately one half within about 1500 days. The "half" recession period of 1500 days (i.e. about 3 years) surely implies that Spain could sustain a drought with effectively no recharge for at least this period. The renewable rate is estimated at 0.13 $year^{-1}$, whereas the renewal period is 7.6 years. From a practical standpoint, this shows the large regulatory potential of the country's aquifer systems.

Reserves amount to approximately four times the average yearly recharge. At the aquifer scale, however, they are highly variable. Just 65 aquifers, whose recharge amounts to 17% of the total, account for 95% of the renewable reserves. These essentially comprise large detritic aquifers such as those in the Duero basin, where groundwater flow is slow, and also the carbonate aquifers in Cuenca, the Júcar basin and the Mancha region, where the large extent of the hydrogeological units counters their relatively high permeabilities. Carbonate aquifers, such as those in the Betic Range or the Guadalquivir basin, are significantly smaller and consequently have less renewable resources.

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